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Effect Of Transverse Weld Feed Rate On Microstructure And Tensile Properties Of FSW Weld Of AA6061

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Abstract: **To accomplish the research objectives set forth for this study, a methodology was developed. The methodology was essentially a model-based approach for optimization of FSW process. The first task was to develop and validate a thermo mechanical model of FSW process in consideration of various published papers as discussed in literature review. The model chosen for this task was the thermo mechanical model developed by Zhu and Chao for FSW of 304L stainless steel. The thermo mechanical model was developed using commercial finite element analysis program ANSYS -14.5. In order to validate the developed model, the output of the model was correlated with the published results. Once developed, the thermo mechanical model was used to simulate the process. The model was then extrapolated to perform parametric studies in order to investigate effects of various process parameters on temperature distribution and residual stress in the work piece.**

The next step was to construct surrogate models using the data generated by the thermo mechanical model. Linear and nonlinear surrogate models were constructed to relate process parameters with responses, i.e., temperature and residual stress measured at selected location. The performance of the developed surrogate models was estimated using several statistical measures. In the next step, constrained optimization models were formulated with goal of maximizing throughput and minimizing manufacturing costs. The optimization models were solved using a traditional nonlinear optimization procedure and a population-based met heuristics, improved harmony search algorithm. Finally, the optimal results were validated by simulation using ANSYS.

I. INTRODUCTION

A weld is made when separate pieces of material to be joined combine and form one piece when heated to a temperature high enough to cause softening or melting. Filler material is typically added to strengthen the joint.

Welding is a dependable, efficient and economic method for permanently joining similar metals. In other words, you can weld steel to steel or aluminum to aluminum, but you cannot weld steel to aluminum using traditional welding processes. Welding is used extensively in all sectors or manufacturing, from earth moving equipment to the aerospace industry.

FSW (Friction Stir Welding) is invented and patented by The Welding Institute, a British research and technology organization, the process is applicable to aerospace, shipbuilding, aircraft and automotive industries. One of the key benefits of this new technology is that it allows welds to be made on aluminum alloys that cannot be readily fusion arc welded, the traditional method of welding.

In 1993, NASA challenged Lockheed Martin Laboratories in Baltimore, Md., to develop a high-strength, low-density, lighter-weight replacement for aluminum alloy Al 2219–used on the original Space Shuttle External Tank. Lockheed Martin, Reynolds Aluminum and the labs at Marshall Space Flight Center in Huntsville, Ala., were successful in developing a new alloy known as Aluminum Lithium Al-Li 2195, which reduced the weight of the External Tank by 7,500 pounds (3,402 kilograms). Today, the External Tank project uses the new alloy to build the Shuttle's Super Lightweight Tanks.

The lithium in the new lighter-weight material—aluminum lithium alloy Al-Li 2195— made the initial welds of the External Tank far more complex. The repair welds were difficult to make and the joint strength of the External Tank had much lower mechanical properties. This drove up production cost on the tank. In an effort to mitigate the increased production cost and regain the mechanical properties of the earlier Al 2219 External Tank the project began researching alternative welding techniques. Because Friction Stir Welding produces stronger welds that are easier to make the External Tank Project Managers chose to use the process on its Super Light Weight Tank, which is made from Al-Li 2195. The Friction Stir Welding process produces a joint stronger than the fusion arc welded joint, obtained in the earlier Light Weight Tank program.

Friction Stir welding (FSW):

In this welding process a solid-state joining process that uses a non-consumable tool to join two facing work pieces without melting the work piece material. Heat is generated by friction between the rotating tool and the work piece material, which leads to a softened region near the FSW tool. While the tool is traversed along the joint line, it mechanically intermixes the two pieces of metal, and forges the hot and softened metal by the mechanical pressure, which is applied by the tool, much like joining clay, or dough. It is primarily used on wrought or extruded aluminum and particularly for structures which need very high weld strength.

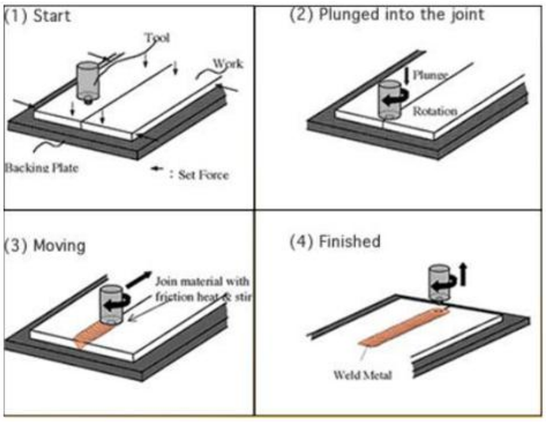

Figure: Friction Stir Welding

II. LITERATURE REVIEW

REVIEW PAPER ON FRICTION STIR WELDING OF ALUMINIUM AND MAGNESIUM ALLOYS by D. Muruganandam (Sri Sairam Engineering College, Chennai), C.Balasubramaniyan (AMET University, Chennai) and B. Gokulachander (AMET University, Chennai).

Methods/Analysis: The Friction Stir Welding of aluminum alloys with magnesiumalloys are reviewed on this paper. The basic principles of FSW are described, followed by process parameters study which affects the weld strength. **Findings:** The microstructure and the likelihood of defects also reviewed. Tensile strength properties attained with different process parameters are discussed. **Conclusion/Application:** It is demonstrated that FSW of aluminum and magnesium alloy is becoming an emerging technology with numerous commercial applications.

EXPERIMENTAL STUDY OF FRICTION STIR WELDING OF 6061-T6 ALUMINUM PIPE by Qasim M Doos and Bashar Abdul Wahab.

The present paper aims to determine the feasibility to weld two pieces of aluminum pipe by friction stir welding process and study the effect on the mechanical properties of welding joints. Special welding fixture fixed on conventional milling machine has been conducted to attempt this welding and group of welding parameters. Three tool rotational speeds (500, 630, 800 rpm) with four welding speeds (0.5, 1, 2, 3 mm/sec) for each rotational speed had been used to study the effect of each parameters (tool rotation, weld speed) on mechanical and microstructure properties of welded joints. Mechanical properties of welded joints were investigated using different mechanical tests including non destructive test (visual inspection, X-ray) and destructive test (tensile test, microhardeness and microstructure). Based on the stir welding experiments conducted in this study the results show that aluminum pipe (AA 6061-T6) can be welded by (FSW) process with a maximum welding efficiency (61.7%) in terms of ultimate tensile strength, using 630 (RPM) rotational speed, 1 (mm/sec) traveling speed.

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A. Scialpi, L.A.C. De Filippis et al (2006):

Investigated the effect of different shoulder geometries on the mechanical and microstructural properties of a friction stir welded joints. The base material used for the process was 6082 T6 aluminium alloy having thickness of 1.5 mm. The three tools studied differed in their shoulder geometries like scroll and fillet, cavity and fillet, and only fillet. The effect of the three shoulder geometries were analyzed by visual inspection, macrograph, transverse and longitudinal room temperature tensile test. The welding process was carried out rotating the tool at 1810 rpm and at a feed rate of 460 mm/min, with a 2o tilt angle and a 0.1 mm plunge. The tool had a non-threaded pin with a 1.7 mm diameter and 1.2 mm height. The fillet was considered because it can reduce stress concentration due to cutting effect and increase the effective contact surface. Shows the TFS, TFC, and TF tools used in the experimentation. Visual inspection of roots and crowns was performed in order to evaluate the shoulder influence on the joint quality. A qualitative analysis of crowns and roots revealed that the roots showed no defects. Figure 3 shows the crowns of the specimens. It was observed that the TFS tool produced a little amount of flash, but the crown is not smooth. The TFC tool produced a smooth surface and very little flash and the TF tool produced smooth crowns and little flashes.

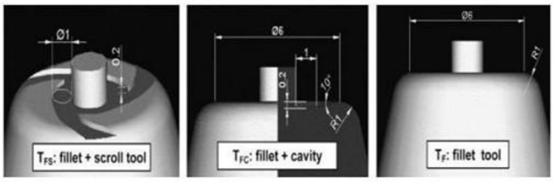

Figure: Tools used for the experimentation and their main dimensions in mm.

III. METHODS & MATERIALS

Friction stir welding can be used for joining many types of materials and material combinations, if tool materials and designs can be found which operate at the forging temperature of the work pieces. Up to the present day, TWI has concentrated most of its efforts to optimizing the process for the joining of aluminium and its alloys. A major Group Sponsored Project undertaken for TWI's Industrial Members demonstrated that the following aluminium alloys could be successfully welded to yield reproducible, high integrity welds within defined parametric tolerances.

- 2000 series aluminium (Al-Cu)
- 5000 series aluminium (Al-Mg)
- 6000 series aluminium (Al-Mg-Si)
- 7000 series aluminium (Al-Zn)
- 8000 series aluminium (Al-Li)

This work primarily investigated welding of wrought and extruded alloys. However, subsequent studies have shown that cast to cast, and cast to extruded (wrought) combinations; in similar and dissimilar aluminium alloys are equally possible.

Continuing development of the FSW tool, its design and materials have allowed preliminary welds to be successfully produced in:

- Copper and its alloys
- Lead
- Titanium and its alloys (see FSW
- Magnesium alloy, Magnesium to aluminium
- Zinc
- MMCs based on aluminium (metal matrix composites)
- Other aluminium alloys of the 1000 (commercially pure), 3000 (Al-Mn) and 4000 (Al-Si) series
- Plastics
- Mild steel

Single pass butt joints with aluminium alloys have been made in thicknesses ranging from 1.2mm to 50mm without the need for a weld preparation. Thicknesses of up to 100mm can be welded using two passes, one from each side, with 6082 aluminium alloy. Parameters for butt welding of most aluminium alloys have been optimized in a thickness range from 1.6mm to 10mm. Special lap joining tools have also been developed for aluminium with thicknesses of 1.2mm to 6.4mm.

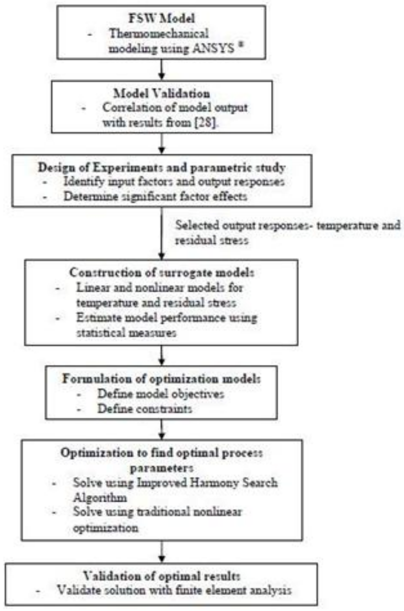

Figure: Methodology of model-based optimization of FSW process

IV. VALIDATION OF THERMOMECHANICAL MODEL OF FRICTION STIR WELDING

For validating the thermomechanical model developed using ANSYS, it was essential to correlate the developed model with the published results. For this purpose, the developed thermomechanical model was verified with numerical results obtained by Zhu and Chao. The model used for validation had dimension of 304.8 mm x 101.6 mm x 3.18 mm of 304L stainless steel material. The tool shoulder diameter was 19.05 mm and the tool pin diameter was 6.35 mm. The tool rotational speed was 300 rpm and the applied downward force was 31.1 KN. The welding was assumed to start at a location 6.4 mm away from the edge of the workpiece and stop after translation of 279.4 mm along the weld line with a velocity of 1.693 mm/s.

V. TEMPERATURE RESPONSES

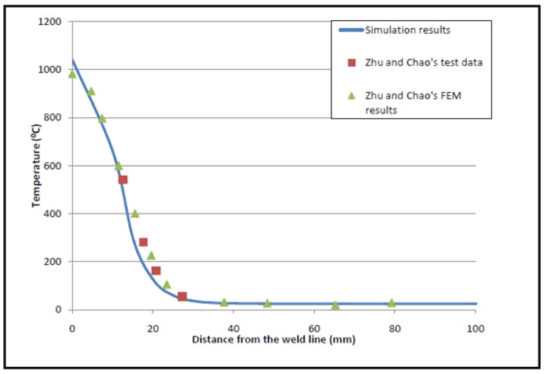

Figure: Comparison of temperature distribution along the transverse direction at welding time t= 83 s

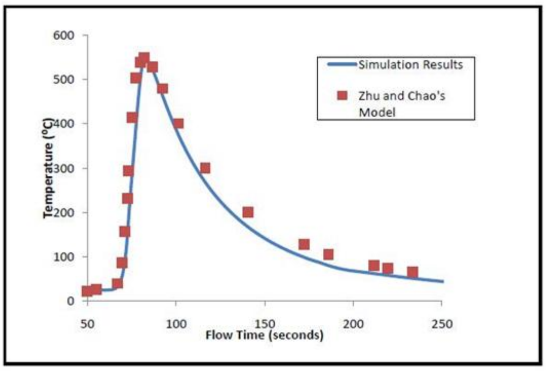

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Figure: Variation of transient temperature - comparison of simulated results and results from Zhu and Chao's Model

VI. STRESS RESPONSES

The temperature fields obtained from the thermal model are used as input for the mechanical simulation for calculation of residual stresses. The primary residual stresses in FSW were observed in the longitudinal direction. Therefore, only longitudinal stresses were considered in this study. Figure 5.4 shows the comparison of results from Zhu and Chao's model and simulation results of longitudinal residual stresses for the top surface. The residual stresses were measured along traverse direction at a distance of 152 mm from the end of the workpiece. Fixture release was modeled in order to estimate the effect of clamping. It was observed that the residual stress in the welds decreased significantly after the fixture release. The overall trend of the developed model for prediction of residual stress is similar to that of Zhu and Chao, thus verifying the validity of the model developed in this study.

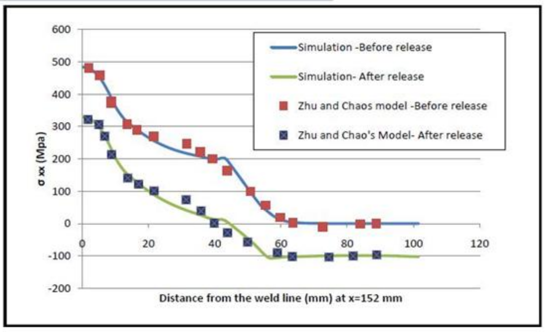

Figure: Variation of the longitudinal residual stress along the traverse direction at the middle section of the workpiece

VII. PARAMETRIC STUDY OF FSW PROCESS

In order to conduct parametric investigation of FSW process, design of experiment methodology is implemented in this study. Design of experiment (DoE) technique is used to optimize the number of experiments required to determine the effects of various factors affecting the response of the system. DoE helps to eliminate the need for extensive experimental analysis and in turn reduces the computational time and cost. The following sections describe the details of DoE and development of surrogate models for FSW process.

VIII. DESIGN OF EXPERIMENTS

Thermal and thermomechanical models developed in the chapter 4 are used as base models for carrying out parametric studies. An "experiment" in this study would refer to a distinct numerical simulation run for a given set of input parameters. The first step in DoE is to identify important independent input factors and response variables. The response variables selected for this study are maximum temperature (T) and residual stress (R). Both these selected responses are recorded at a selected location i.e. X= 152.4 mm, Y= 0 mm, and Z= 0 mm. The process parameters heat input (H) and welding speed (S) are chosen as input variables affecting the response variable temperature (T), while the parameters H, S and clamping location (C) are chosen variables affecting the response residual stress (R). The next step is to identify the range and the specific levels at which selected factors have to be varied. Table 6.1 lists the process parameters, their range and selected levels used in this study for response variables T and R.

The final step in the parametric design is to perform the required number of experimental runs and analyze the significant factor effects. The total number of experimental runs to be conducted is identified from the total number of factors and the number of levels selected. Table A.1 in appendix A depicts the design matrix for response variable T used in screening design for parametric study.

Table A.2 in appendix A depicts the design matrix for the other selected response, residual stress (R). The observations which exceeded 1450 ℃, the melting point of 304L stainless steel, were omitted from design matrix when formulating surrogate models.

Response	Process Parameters	Units	Range	Level 1	Level 2	Level 3	Level 4	Level 5
Temperature (T)	Weld Speed (*S*)	mm/sec	0.5-2.54	0.5	0.85	1.00	1.69	2.54
	Heat Input (*H*)	watt	500-970	500	600	760	970	-
Residual Stress (R)	Weld Speed (*S*)	mm/sec	0.5-2.54	0.5	0.85	1.00	1.69	2.54
	Heat Input (*H*)	watt	500-970	500	600	760	970	-
	Clamping location (*C*)	mm	50.2-76.2	50.2	76.2	-	-	-

Table: Process parameters, range and design levels used

IX. VALIDATION OF OPTIMIZATION RESULTS

In order to validate the optimization results, finite element analysis (FEA) simulations were carried out according to the process parameters that were obtained from the optimization scheme. Table presents the summary of optimal results obtained for different cases for response variable, temperature. The results indicate that the developed models were able to predict the temperature with a reasonable accuracy.

			Temperature Constraint Range	
			1000-1300	1050-1150
Optimal Solution		Heat Input(W)	772.970	779.8538
		Weld Speed(mm/s)	2.312	2.162
		Clamping Location (mm)	50.2	50.2
Model		Best Model	Model 4	Model 4
		Regression Type	Nonlinear	Nonlinear
Output	Temperature (°C)	Model Predicted	1021.618	1069.978
		FEA Simulation	991.216	1036.87
		Error %	3.0671	3.1930
	Residual Stress (*MPa*)	Model Predicted	309.9971	309.9973
		FEA Simulation	316.597	323.247

Table: Summary of results for responses - temperature and residual stress

X. CONCLUSION

In this project a thermomechanical model of friction stir welding process was reproduced and a surrogate model-based optimization scheme was implemented to obtain the optimal parameters for the process. The thermomechanical model selected for implementation was developed by Zhu and Chao for friction stir welding of 304L stainless steel. The selected finite element model was replicated using ANSYS APDL and validated with the published results. The validated model was then used to simulate the process. A design of experiments and parametric study were performed to identify the effect of various input parameters like: heat input, welding speed and clamping location on temperature distribution and residual stress in the workpiece. Later, linear and nonlinear surrogate models were developed using regression analysis to relate the selected process input parameters with the response variables. Finally, constrained optimization models were formulated using surrogate models with the goal of maximizing throughput and minimizing cost under constraints of achieving desired weld quality and satisfying the operating constraints. The optimization problems were solved using the improved harmony search algorithm enhanced with the parameter-less penalty method proposed by Deb to handle the constraints.

Based on the models developed, the parametric studies and the optimization results, the following observations were made:

1. From the parametric study, it was observed that the workpiece temperature decreases as the welding speed increases, while the residual stress first increases with increase in welding speed and then tends to slightly decrease at higher welding speeds.
2. Clamping location has significant effect on the level of residual stress developed. It was observed that clamping workpiece far from the weld resulted in higher residual stresses.
3. When solving all the optimization models, it was observed that IHS+ was not able to converge to the best solution in many runs. Nevertheless, the average solution found in all runs was very close to the best. Further, from practical point of view this deviation from optimal might be relatively less than accuracy of the physical system and hence might be insignificant in practice.
4. Optimization models formulated in this study were solved easily by *fmincon* function utilizing gradient based technique. However, IHS+ could be useful to solve more complicated problems involving discrete variables where conventional gradient based techniques cannot be applied.
5. The optimum parameters for FSW process were obtained and summarized in table 6.2. These optimal solutions were verified by the results obtained from finite element analysis.
6. Optimization results show that in order to minimize the objective value, welding speed must be maintained at its maximum value while keeping heat input as low as possible.

XI. RECOMMENDATIONS FOR FUTURE WORK

For future work, experimental investigations need to be carried out to verify the numerical simulations and optimal solutions obtained in this thesis. The process variables used in this study were limited to responses, maximum temperature and residual stress and the following input variables: heat input, weld speed, and clamping location. The optimization can be performed on a process model that includes more input process variables and output responses. The materials to be welded are considered identical in this study. Similar studies can be extended to other variants of friction stir welding processes such as laser-assisted friction stir welding process, or the welding of dissimilar materials that will be technically more challenging due to the differences in material properties. More comprehensive thermal-material-mechanical models could also be considered for optimization.

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